SPINE for DUNE and its Prototypes

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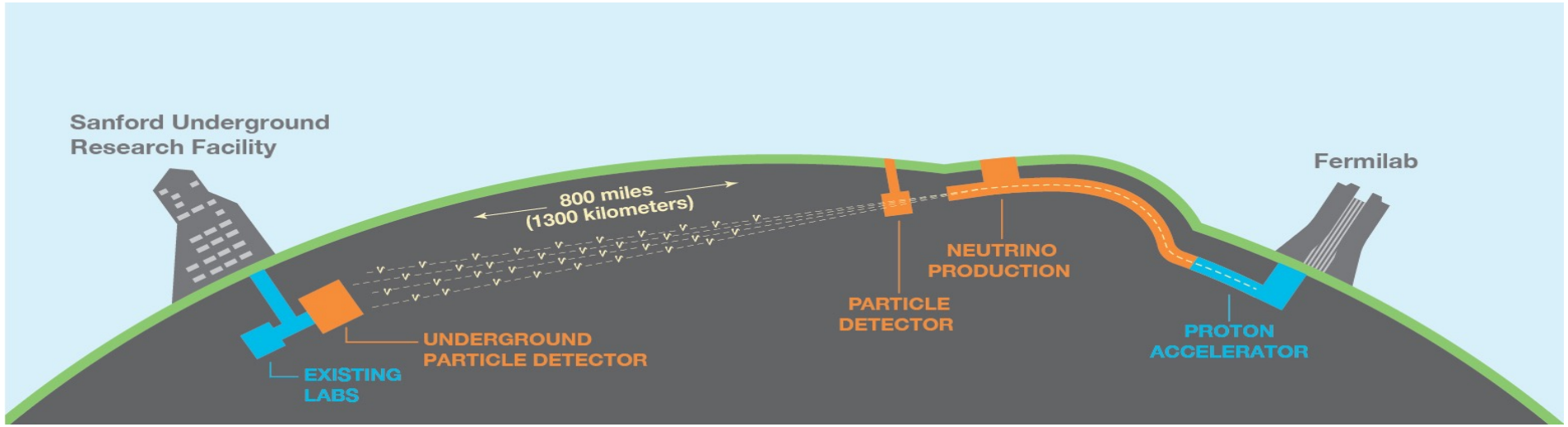
02/04/2026

The Deep Underground Neutrino Experiment

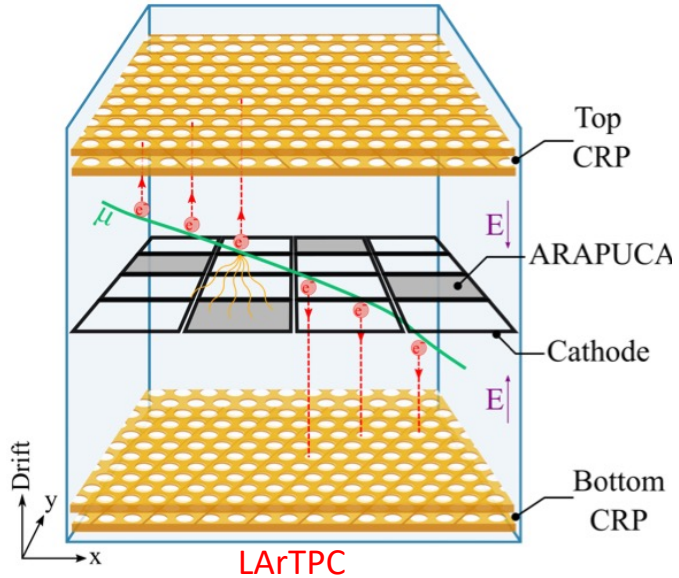


- DUNE is a next-generation long-baseline neutrino experiment designed to study neutrino oscillations and fundamental properties of matter.
- Long-baseline configuration spanning **1300 km** from Chicago to Sanford underground research facility , enables an unambiguous measurement of the MO (no degeneracy between CPV and matter effect)
- World's most powerful neutrino beam (>2 MW) produced at Fermilab
- Far detector located **1.5 km underground** for strong cosmic background suppression and near detector complex positioned **~560 m from the neutrino source**
- **High-resolution 3D tracking and calorimetric reconstruction enabled by LArTPC technology**
- Four liquid argon TPC far detector modules with a total mass of **~70 kton**

DUNE Far detector and prototypes

- We focus on the DUNE far detector and its CERN prototypes: ProtoDUNE-SP and ProtoDUNE-VD
- These are liquid argon TPCs (LArTPCs), providing high-resolution images → ideal for machine learning
- LArTPCs have three wire planes, but reconstructing 3D information from 2D wire data is challenging
- We use a dedicated spacepoint producer to build 3D spacepoints from wire signals
- This process introduces false points, known as “ghosts”
- First reconstruction step: remove these ghost points
- Then we apply **SPINE**, a flagship ML-based reconstruction pipeline for full event reconstruction

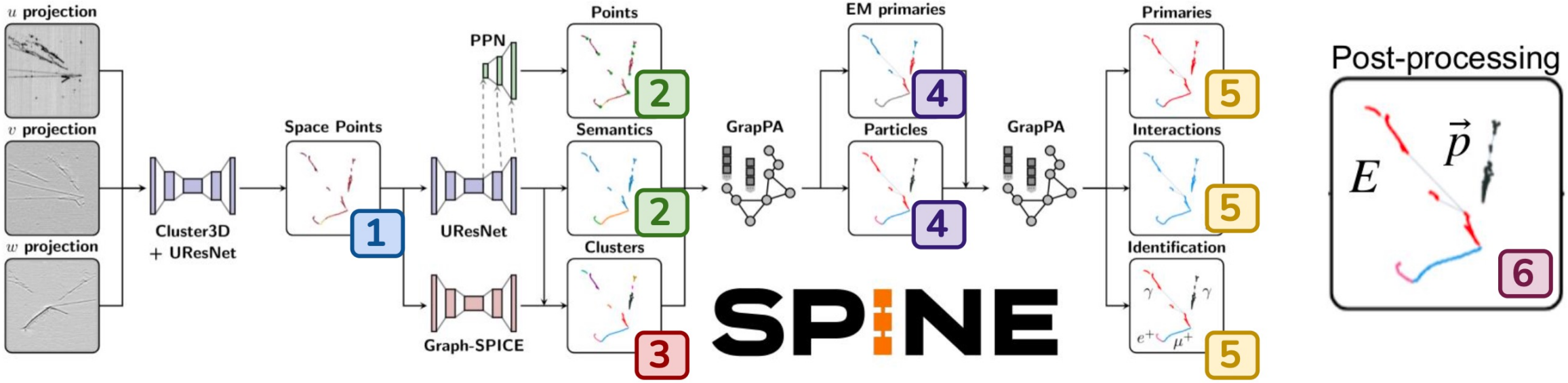
Cern neutrino platform



LArTPC

https://github.com/DeepLearnPhysics/spine/tree/main

Scalable Particle Imaging with Neural Embeddings



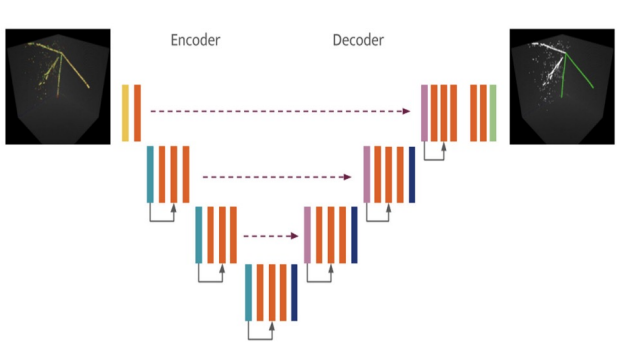
A fully trainable pipeline that takes raw 3D detector hits, groups them into higher level structures like particles or interaction vertices, and assigns each structure a semantic or particle type label.

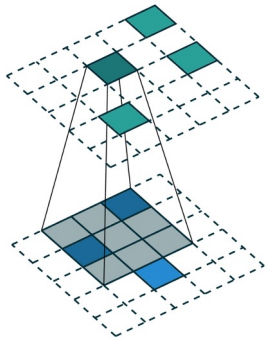
- All the work presented in this presentation was shared by me at the SPINE Workshop 2026 held at CERN in February.

https://github.com/DeepLearnPhysics/spine-workshop-2026/tree/main

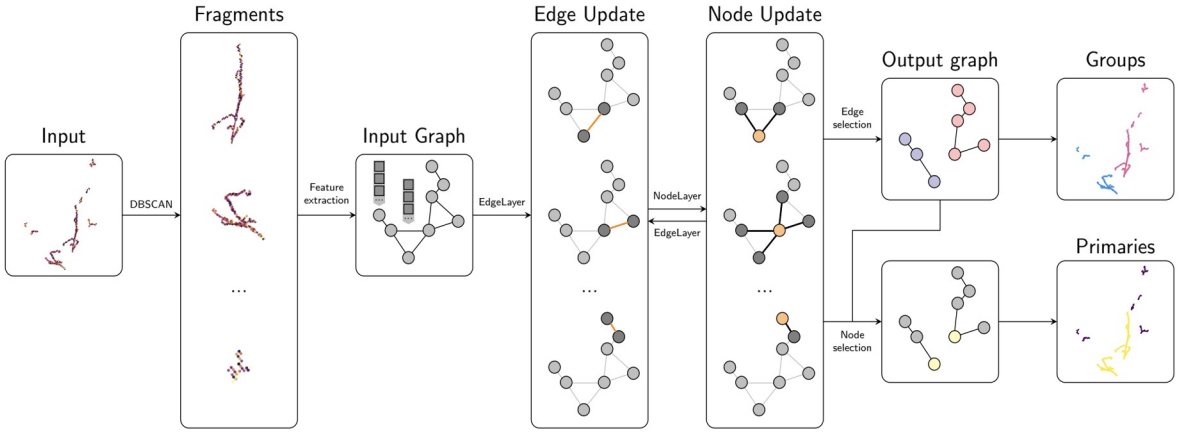
SPINE has mainly 2 architectural back bones

- **UResNet backbone:** handles low-level reconstruction tasks — semantic segmentation, vertexing, and fragment clustering
- **GRAPPA (GNN-based):** performs higher-level clustering by grouping fragments into complete particle tracks and interactions



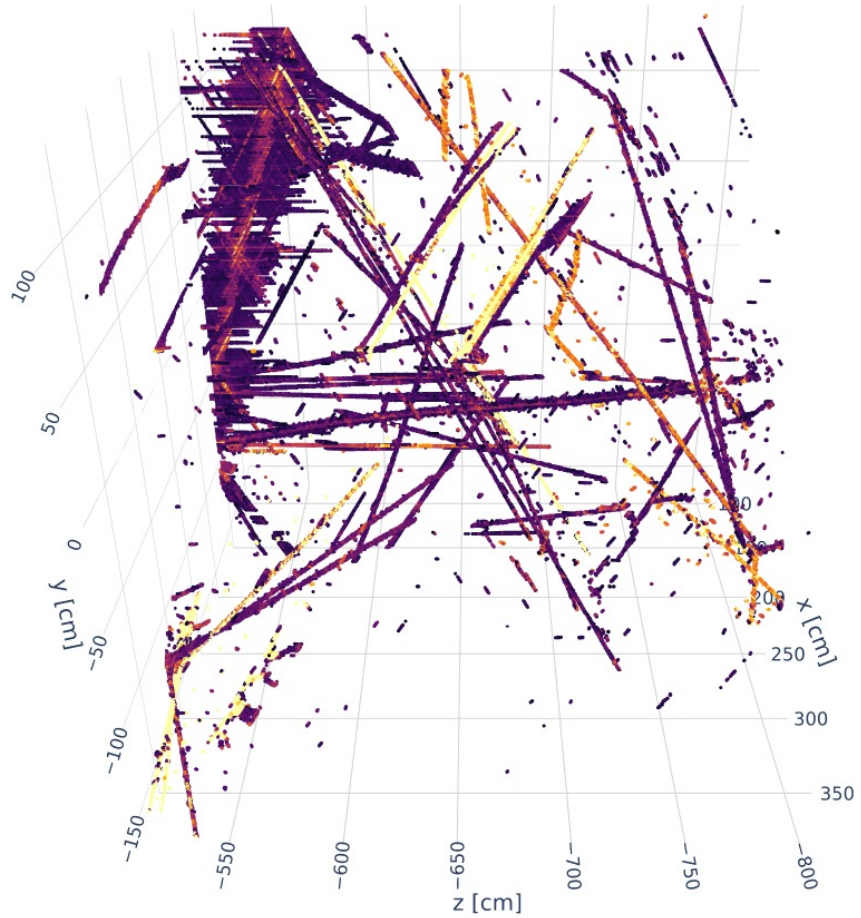


UResNet

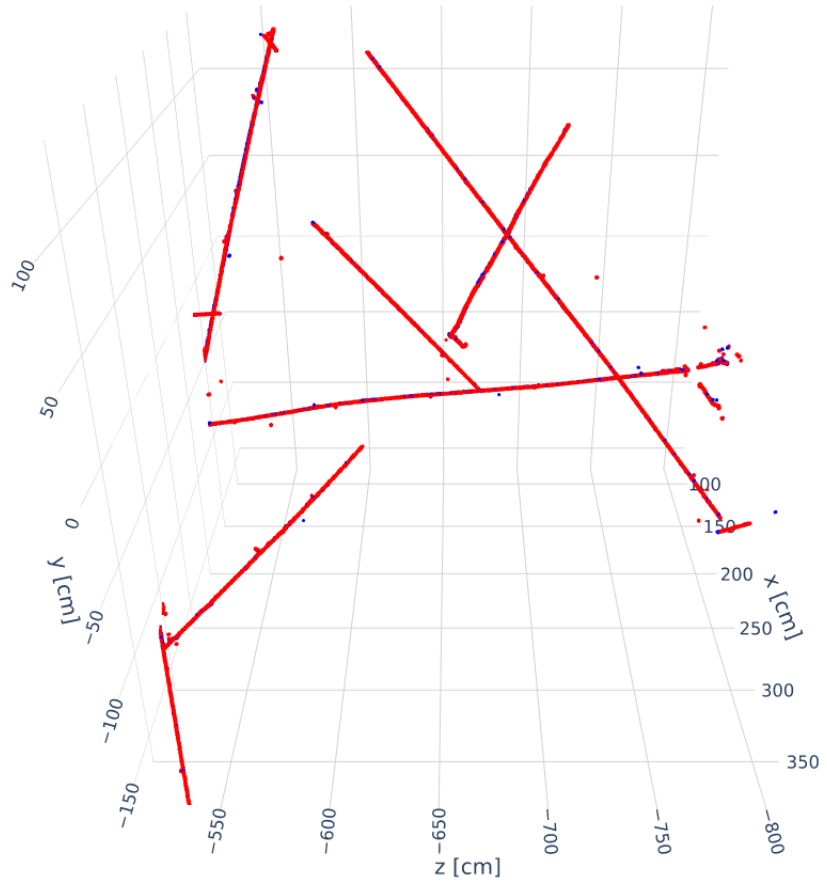


GRAPPA

- Each branch of the pipeline is trained independently using the required ground-truth labels
- A final transfer training step is performed on the full chain to ensure end-to-end consistency
- Model weights are hosted on SLAC Kubernetes for scalable access and deployment



Cluster3d output



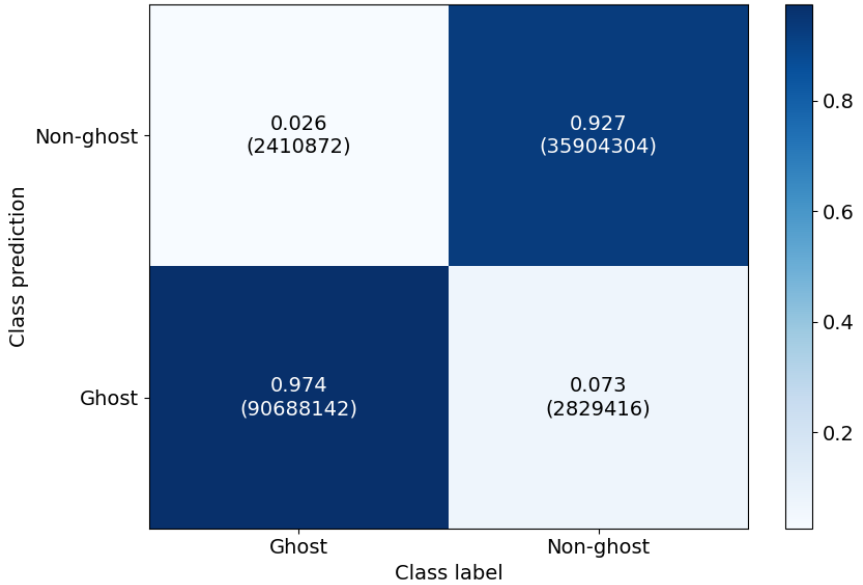
Deghosted image

TRAINING SPINE FOR PDVD

- The network was trained with 350K events
- We use a custom event generator for SPINE training that produces unbiased particle guns and bombs across random directions and energy ranges

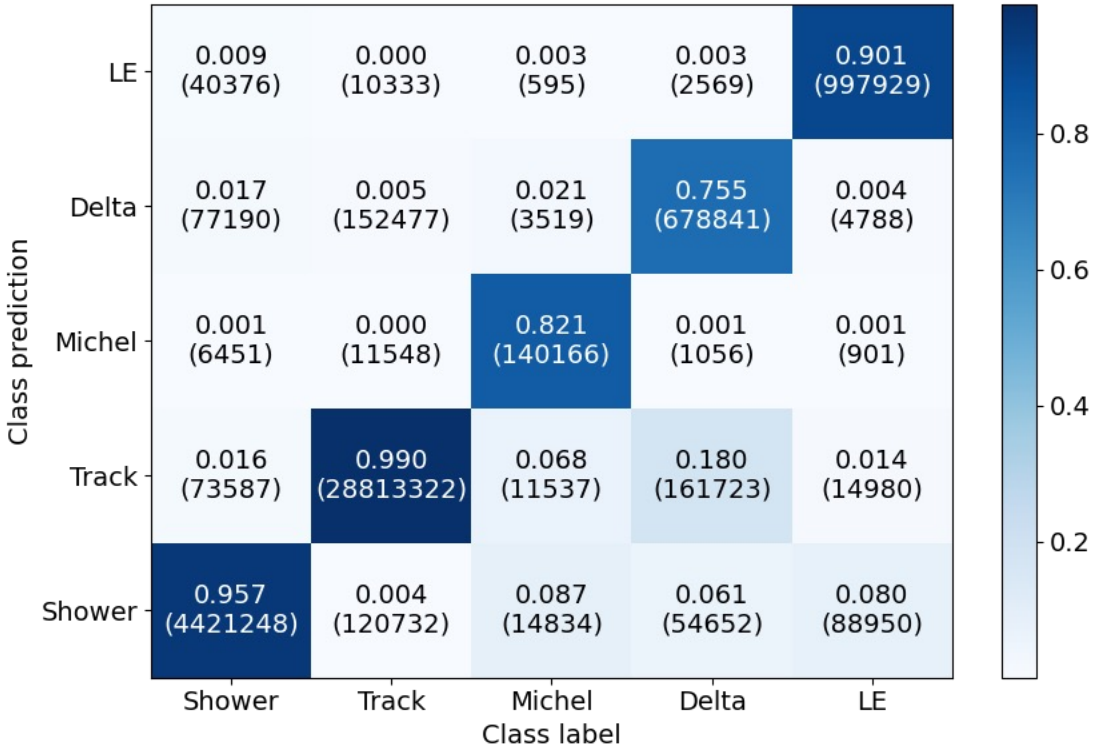
Results

Deghosting



Ghost point separation

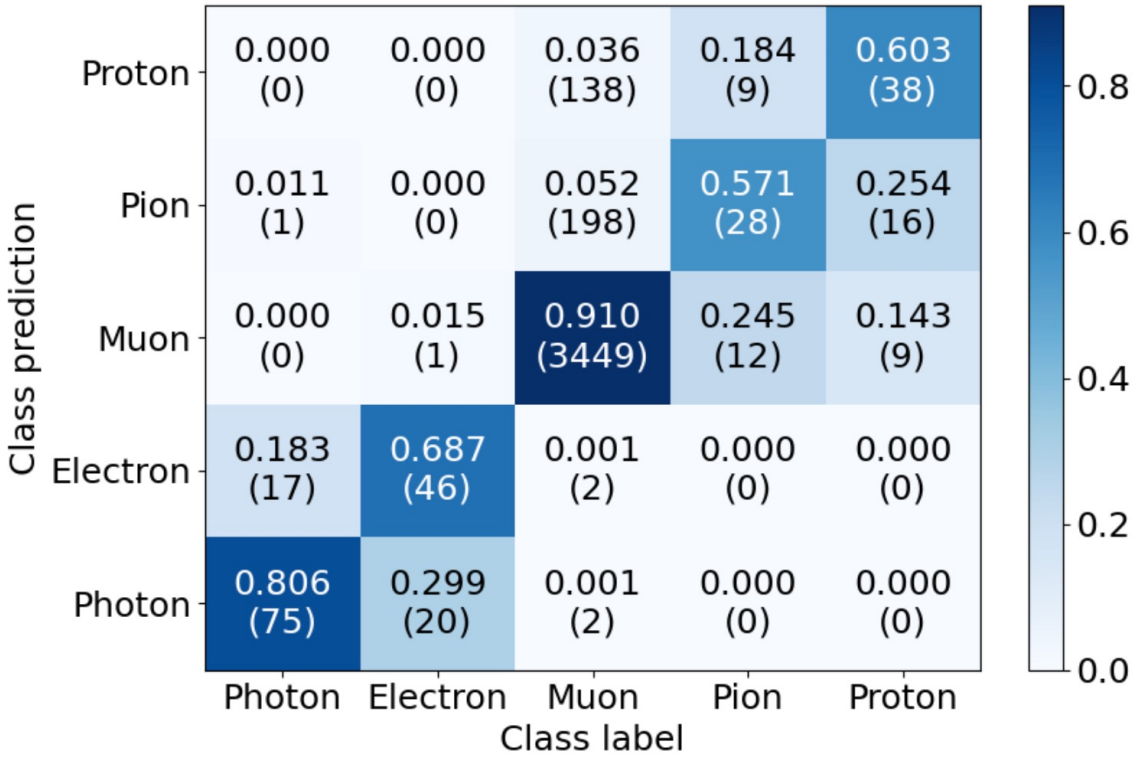
Semantic segmentation

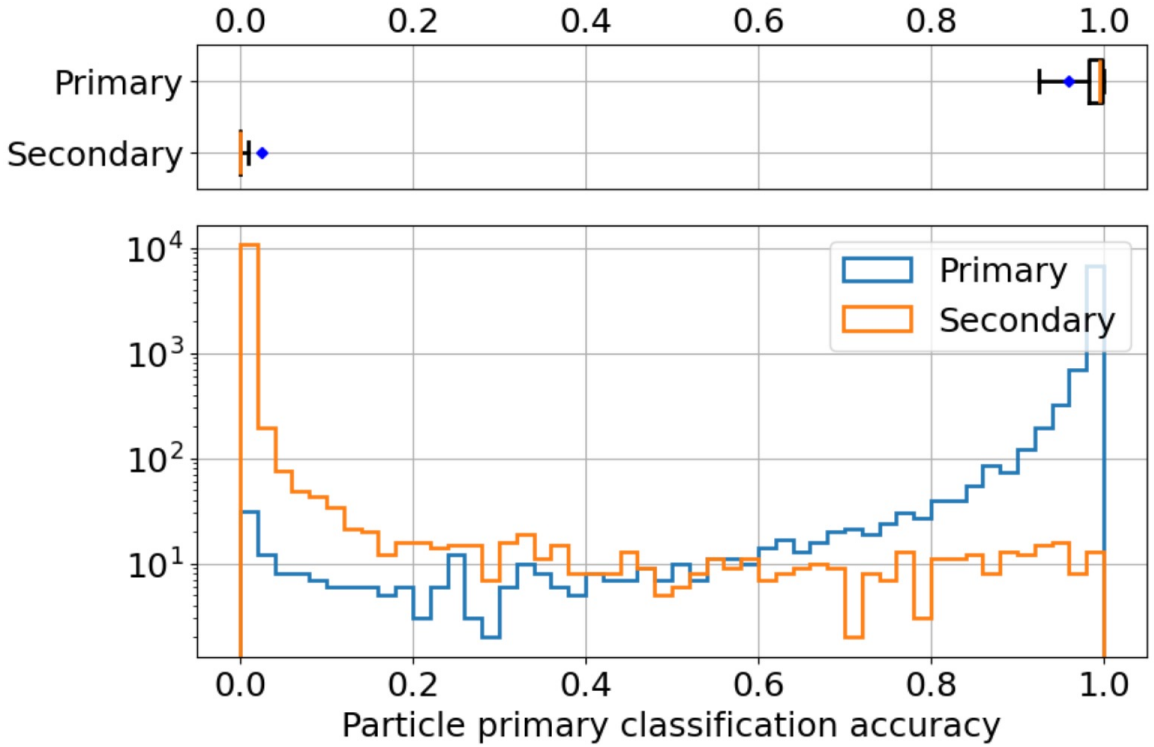


Separation into **topologically different** types of activity

Particle clustering and PID

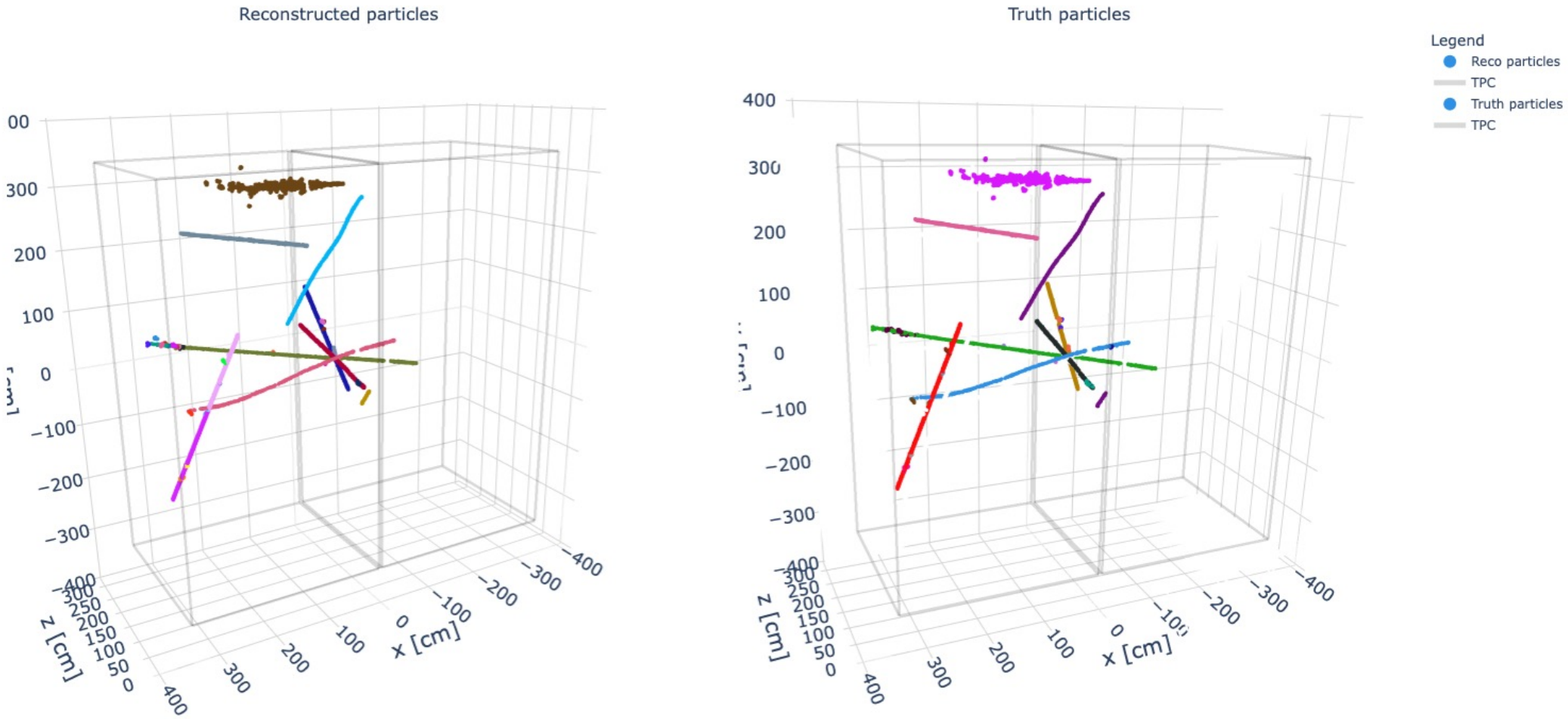
The final SPINE branch (GRAPPA-Inter) provides PID and primary particle performance.





Primary performance ≈ 97%

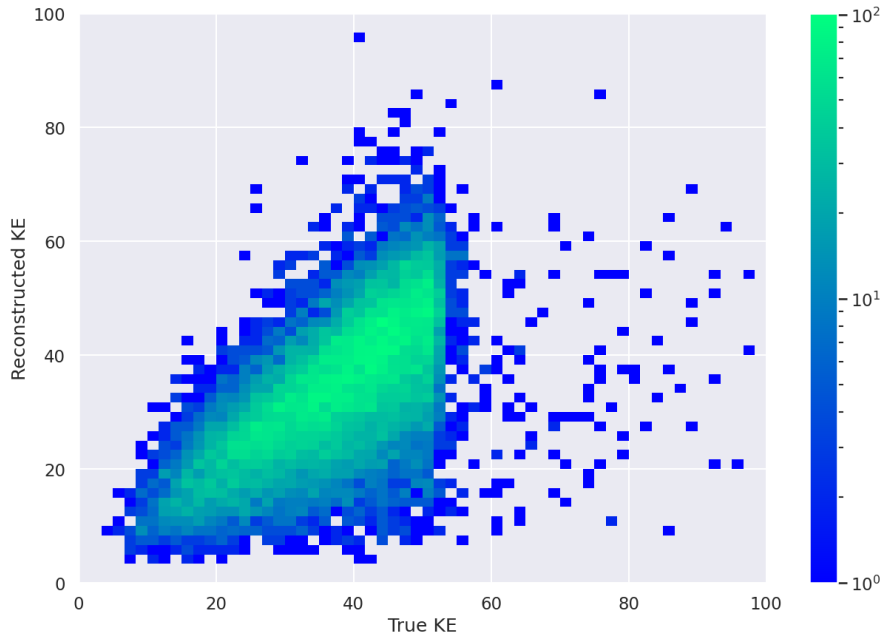
(percentage of correctly identified primaries)



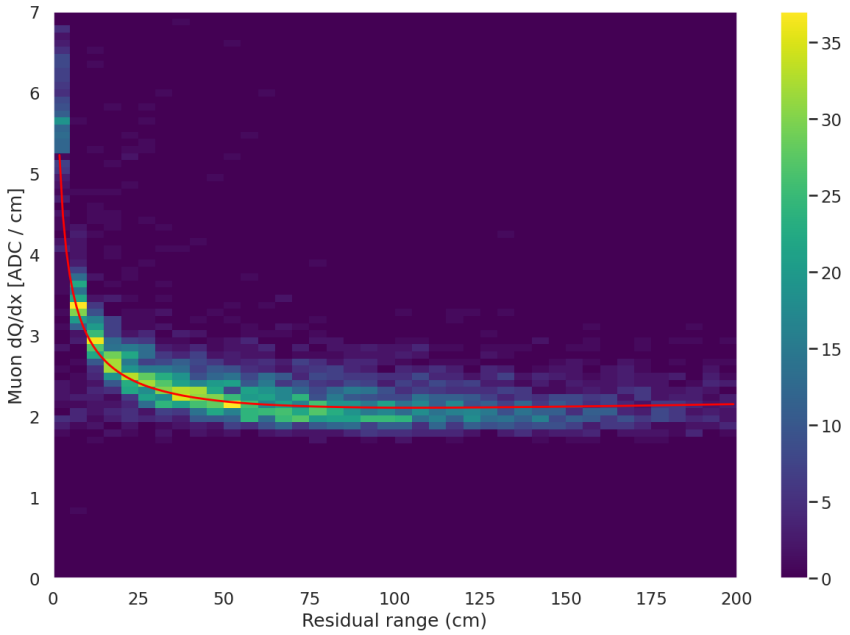
True vs. reconstructed particles in PDVD MPVMPR events using SPINE.

PDVD Cosmic sim

We test higher-level calibration parameters, such as Michel electron reconstruction efficiency, stopping track dq/dx



Michel



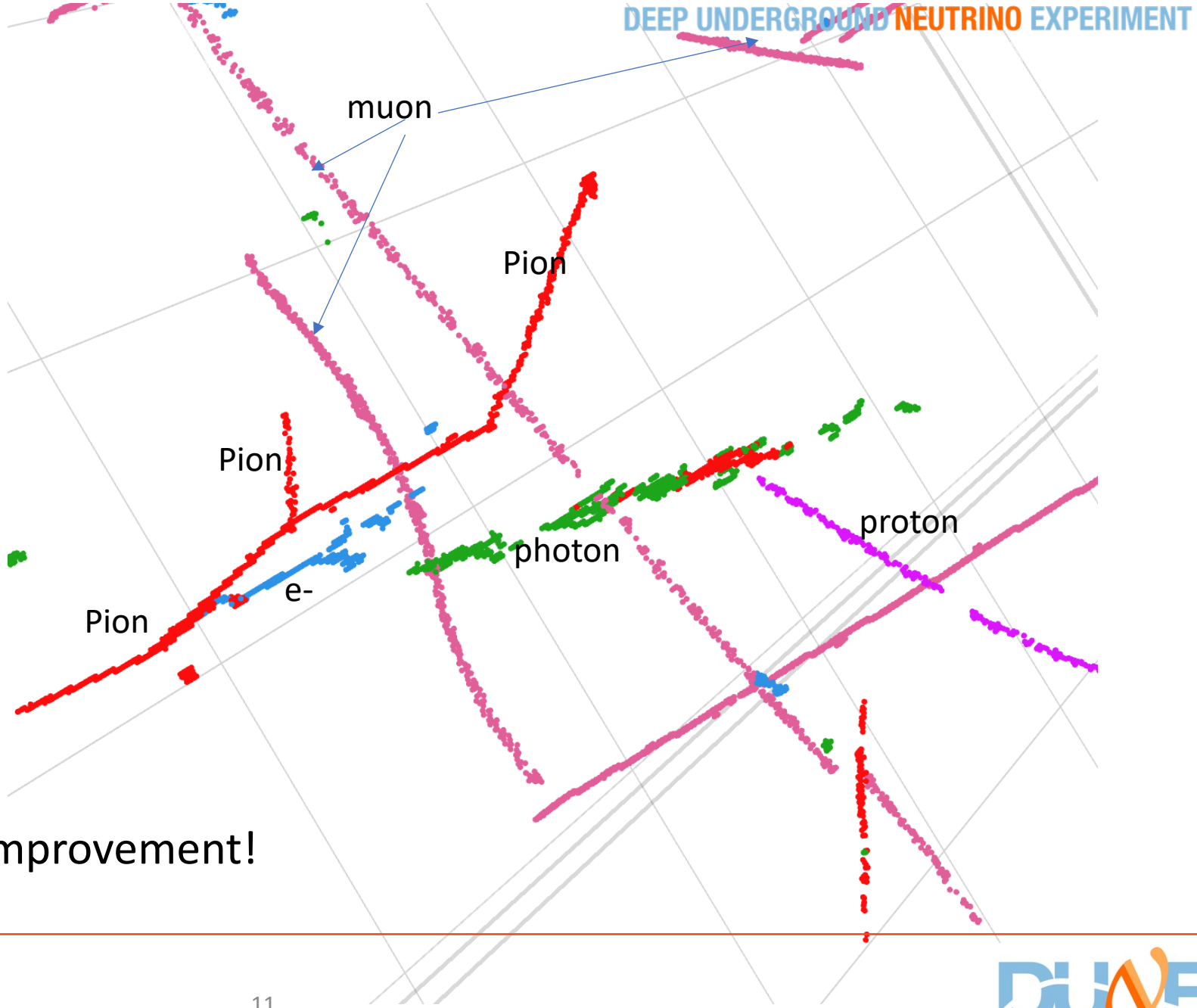
dq/dx

Michel Identification purity = 87.04 % Identification efficiency = 79.81 %

→ The consistency of these distributions with expectations validates the performance of SPINE at the reconstruction level.

https://github.com/DeepLearnPhysics/spine-workshop-2026/tree/main/reconstruction/

A Beam event!



Shower clustering PID needs improvement!

THANK YOU FOR LISTENING!